

Satellite Contributions to the Ocean Observing System for Climate, 2008 -2009

Kenneth S. Casey, Tess B. Brandon, NOAA National Oceanographic Data Center
Laurence N. Connor, Eric Leuliette, John Lillibridge, Laury Miller, Paul DiGiacomo, Paul Chang,
Zorana Jelenak, NOAA Center for Satellite Applications and Research
Linda Stathoplos, NOAA Office of Satellite Data Processing and Distribution
Florence Fetterer, Walt Meier, National Snow and Ice Data Center
Ron Weaver, National Snow and Ice Data Center and Univ. of Colorado
Pablo Clemente-Colón, U.S. National Ice Center

Introduction

During 2008 and 2009, the importance of long and accurate measurements from ocean-observing satellites continued to grow. The ability of space-borne sensors to observe the global ocean frequently and at a fine spatial resolution, when coupled with accurate in situ observations both at the surface and at depth, provides critical information needed to understand the global climate system. Since the time of the last report, satellite observing systems have continued to meet the continuity requirements for building climate data records (CDRs), but are facing growing challenges as the existing instruments age and newer systems under development face delays. The Jason-2 satellite is successfully continuing the ocean surface topography observational record, but the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument for ocean color spent much of its time in safe-hold during the last year. The Moderate-resolution Imaging Spectroradiometer (MODIS) sensor on the NASA Aqua satellite has performed well in its place but is itself also aging, presenting growing challenges for the ocean color community. Satellites still successfully monitor sea ice, and the last year has seen continued growth and coordination within the satellite sea surface temperature (SST) community.

Readers familiar with the past annual reports will notice that we again omit the historical descriptions and rationale for each of the parameter classes. Readers interested in those relatively static pieces of information may refer to earlier versions of this report. With the growing importance of international coordination in the ocean remote sensing community, this year's report will begin with a review of the Virtual Constellations (VC) being organized by the Committee on Earth Observing Satellites (CEOS). We will then include updates on the latest status, critical activities, and a look forward to the future for SST, ocean color, ocean surface topography, and sea ice. Finally, we also include an update on the status of marine winds, which was not included in last year's report.

CEOS Virtual Constellations

Given the expense and complexity, no single satellite mission, agency, or nation can satisfy all of the observational requirements necessary to understand the Earth System. A lack of coordination and common requirements has often resulted in an *ad-hoc* approach to space-based Earth observation. In 1984, CEOS was created to provide a forum for worldwide coordination of these programs in order to maintain continuity of observations, minimize redundancy, identify and address information gaps, and build and sustain a truly global Earth observation network. The CEOS Virtual Constellation (VC) concept is a mechanism designed to facilitate this coordination.

The concept involves multiple satellites from multiple agencies working in harmony to improve temporal, spatial and spectral resolution, enhance system compatibility, and increase data availability. At the center of the VC concept is a clear and common set of standards required for any mission's inclusion in the constellation, including guidance on the characteristics of the space and ground segments for that mission that would enable it to best satisfy the needs of the user community. As of fall 2008, six prototype VCs have been approved for development, including three with ocean applications. These include the Ocean Surface Topography Constellation, which is a NOAA/EUMETSAT effort designed to ensure continuity of sea level measurement; the Ocean Color Radiometry Constellation, which will provide calibrated ocean color radiometry for ocean biology and biogeochemistry applications and currently has participation from more than 10 agencies internationally; and the Ocean Surface Vector Winds Constellation, which will improve operational marine warnings and forecasts through the use of satellite scatterometry and input from other VCs and the Group for High Resolution SST (GHRSSST) program. In the spring of 2009, GHRSSST also agreed to pursue designation within CEOS as the VC for SST. The outputs of these VCs, when joined with *in situ* observations, will considerably improve the extent to which various agency programs can meet the continuity and accuracy requirements for climate monitoring of the oceans from space.

Sea Surface Temperature

Current Status and a Look Forward

SST remains one of the most critical parameter for ocean climate monitoring, with a continuous record of satellite monitoring dating back to 1981. Currently, the MODIS sensors on the NASA Terra and Aqua platforms continue to perform well and the Advanced Very High Resolution Radiometers (AVHRRs) on board Metop-A, NOAA-18 and NOAA-19 are in operational status. The Geostationary Operational Environmental Satellite (GOES) platforms, GOES-11 and GOES-12, continue to deliver SST measurements, as do the Advanced Along Track Scanning Radiometer (AATSR) on board the European Space Agency (ESA) ENVISAT satellite, the Tropical Rainfall Measuring Mission (TRMM) and its TRMM Microwave Imager (TMI), the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) on board the NASA Aqua platform, and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation (MSG) satellite series. Other platforms are also currently making SST observations.

Later in 2009, the Republic of Korea plans to launch its first Communication, Ocean, and Meteorological Satellite (COMS) into geostationary orbit. COMS will be capable of observing SST and ocean color. Looking further forward, the next generation National Polar-orbiting Operational Satellite System (NPOESS) program and its pre-cursor NPOESS Preparatory Project (NPP) will carry the Visible-Infrared Imager-Radiometer Suite (VIIRS), the successor to the AVHRRs and the MODIS sensors. NPP and the first NPOESS satellite are currently planned for launch in 2011 and 2014, respectively. The AMSR2 instrument on board the Japanese GCOM-W platform, expected to launch in 2012, will extend the time series of the current AMSR-E. From ESA, the pair of Sentinel-3 satellites will each carry Sea and Land Surface Temperature Radiometer (SLSTR) instruments, designed to continue the AATSR time series after their launch in 2012. Finally, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is planning for a 2012

launch of the second in the MetOp series of satellites, MetOp-B, which will carry the last of the AVHRR sensors.

Critical Activities

As in the past, consistently reprocessing individual sensor observations, combining multiple contemporaneous observations from different sensors, and merging time series from individual sensors into a consistent record remain high priority areas for SST climate record development. Since the time of the last report, there have been several important advances in these areas. International coordination of these activities has been achieved through the Group for High Resolution SST Pilot Project (GHRSSST), formerly known as the GODAE High Resolution SST Pilot Project (GHRSSST-PP; Donlon et al., 2007), which became active in 2002 and is now producing and distributing over 30 commonly formatted SST products, all with error uncertainties (<http://www.ghrsst-pp.org>). GHRSSST has matured into a global operational “system of systems” and delivers both near real time operational products like the global ODYSSEA product (Figure 1, Autret and Piollé, 2008) as well as retrospective, reprocessed data sets like the NOAA National Climatic Data Center’s Daily OI (<http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php>, Reynolds et al., 2007), which extends from present back to 1981 and relies on the reprocessed AVHRR Pathfinder time series.

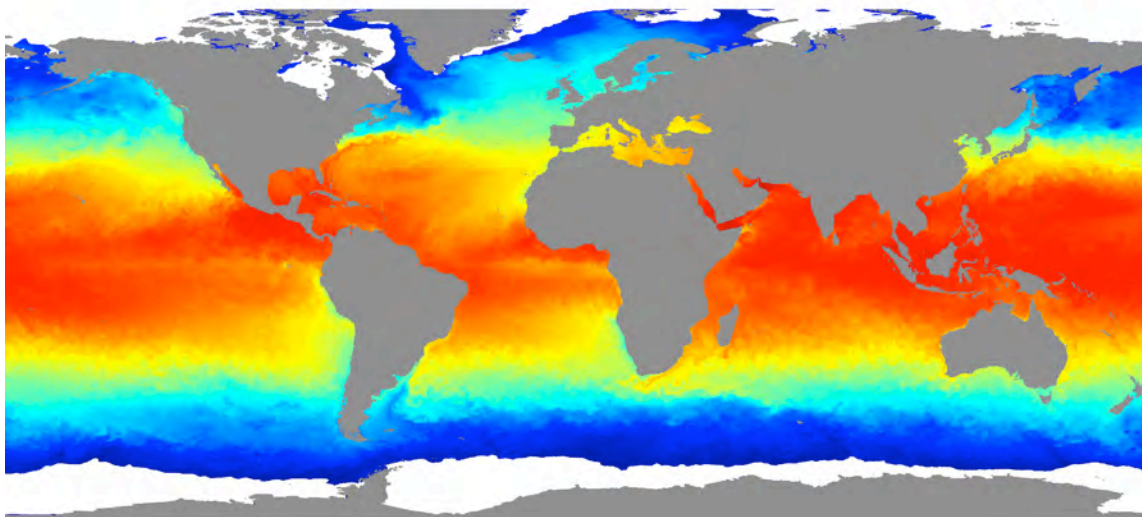


Figure 1: Global ODYSSEA Sea Surface Temperature Analysis for June 11, 2009, from the GHRSSST program. ODYSSEA is a daily, global, Level 4 gap-free analysis product produced at IFREMER/CERSAT (France), and has a spatial resolution of 10 km. The ODYSSEA system is also used regionally to produce high-resolution (1-2 km) products for specific areas of the globe.

NOAA’s National Oceanographic Data Center (NODC) and the University of Miami continue to maintain and develop the AVHRR Pathfinder data set, the single-sensor series reprocessing effort focused on creating global SST CDRs from the AVHRRs on the NOAA polar orbiters (<http://pathfinder.nodc.noaa.gov>). Early in 2009, the Pathfinder project reached a major milestone and for the first time extended its global, approximately 4 km resolution time series back to 1981 with data from the NOAA-7 satellite. Pathfinder SSTs are now available for 1981-2008 on multiple averaging periods (daily, 5-day, 7-day, 8-day, monthly, and yearly) with corresponding

climatologies. Efforts are now focused on the transition to AVHRR Pathfinder Version 6, which will feature key improvements over Version 5, including a higher resolution reference field. This improved reference field will increase data retention in coastal and high gradient regions and in regions where meandering or feature advection is present. Also, output from Version 6 will adhere to the international GHRSSST content and format standards, including uncertainty estimates, which are an important requirement for a CDR.

While single-sensor reprocessing efforts like Pathfinder are critical, no single product, from satellites or from *in situ* platforms, can fulfill the wide range of requirements generated by the various ocean and climate applications of SST. Instead, a diverse but coordinated collection of efforts is needed to generate a suite of products that, together, comprise the complete SST Essential Climate Variable (ECV). Building upon the Global Climate Observing System (GCOS) climate monitoring principles, the NOAA Scientific Data Stewardship Program and Climate Data Record Project, the ESA Climate Change Initiative (CCI), and other statements of climate data requirements, the international GHRSSST community has developed a framework for the SST ECV (Figure 2). The framework is intended to help organize the community's related activities from around the world, identify the gaps, understand what parts are being done well now, and provide direction for future priorities.

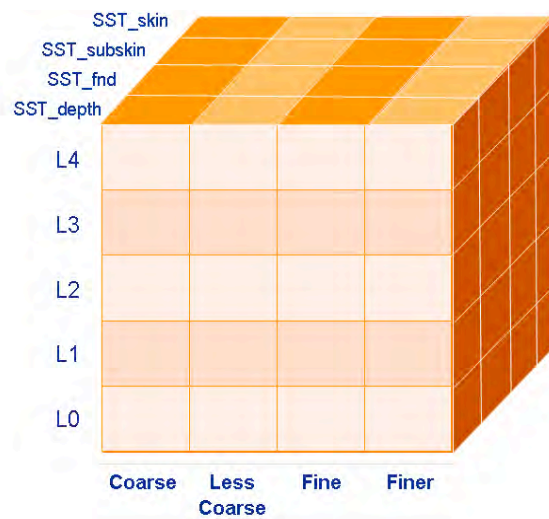


Figure 2: Conceptual framework for the SST ECV illustrating that the many different user requirements for the SST ECV result in a need for an interconnected and coordinated suite of SST ECV products and services.

The framework defines a suite of SST products that align themselves along three dimensions: SST type (skin, subskin, foundation, or at depth), processing level (from Level 0, or “raw” data, to globally-complete Level 4 analyses), and spatio-temporal resolution. To link the suite together into a cohesive ECV framework, each of the products must meet a set of overarching requirements defined by scientific data stewardship and CDR principles. Addressing every element of this SST ECV framework is an enormous task that is outside the scope of any single group. Instead, the SST ECV requires a globally coordinated approach, in which individual efforts recognize their connection to the other parts of the framework, as well as to other related ECVs such as sea ice, clouds, and aerosols.

Ocean Color

Current Status and a Look Forward

Satellite-based ocean color observations are invaluable in climate studies; they help improve our understanding of ocean biology and biogeochemistry and the significant role of the ocean in the

global carbon cycle. Ocean color data also help evaluate the impacts of climate change on coastal and ocean ecosystems, including influences of climate on eutrophication, harmful algal blooms, primary productivity, fisheries, and protected habitats. Accurately measuring ocean color properties remains, however, a demanding task. Key challenges include the need to correct for significant atmospheric effects, as well as to discriminate the various optical constituents, particularly in complex and dynamic coastal waters. Despite these challenges, there has been a continuous climate-quality ocean color time series since 1997. The continuity of this climate-quality time series is currently at risk.

In this regard, NOAA is presently pursuing a satellite mitigation plan to help maintain continuity of SeaWiFS-quality data, with a more comprehensive Analysis of Alternatives (AoA) study to take place in late 2009 that will also explore sub-orbital and *in situ* options. Additionally, NOAA, along with NASA, the National Science Foundation, and the U.S. Navy Office of Naval Research have initiated plans for a National Research Council (NRC) study that will start in 2009 and provide guidance for a sustained global ocean color measurement capability that enables continuity with previous observations and supports climate research and operational requirements. In particular, this NRC study will identify the research and operational needs and the associated sensor and system requirements for a sustained, systematic capability to observe ocean color from space; review the capability of current and planned national and international ocean color radiometry sensors - including VIIRS and foreign alternatives - in meeting these requirements; and assess the gaps and options for filling gaps between the current/planned sensor capabilities and the requirements. The NRC plans to complete this activity in FY 2010.

SeaWiFS has been operating in “safe haven”, a non-imaging mode, for much of 2008 and 2009 as a result of internal telemetry and navigation anomalies. The sensor itself, however, remains healthy and fully functional. Since SeaWiFS is commercially owned, availability of SeaWiFS data depends on purchasing licenses. NASA has maintained access to delayed, reduced resolution global data; NOAA has maintained access to near-real time full resolution data for U.S. East Coast waters only. Fortunately, ocean color observations from MODIS-Aqua have been fully calibrated and now provide global data with quality comparable to SeaWiFS; the Aqua ocean color time-series runs from 2002 to the present. Efforts continue to address issues that have been identified with use of MODIS-Terra for ocean color applications (Franz et al., 2008); a reprocessed MODIS-Terra dataset is expected to become available later in 2009.

In Europe, the Medium Resolution Imaging Spectrometer (MERIS) on Envisat-1 has been operating since 2002 and is currently providing high quality data for a variety of applications. NOAA began producing CoastWatch ocean color products operationally for U.S. coastal waters from MERIS reduced resolution (1 km) data in January 2009 (Figure 3). However, ESA does not consider Envisat to be an operational mission, which impacts data latency and data access. A follow-on to MERIS is currently being developed: the Ocean and Land Colour Instrument (OLCI) on the Sentinel-3 platforms. These missions will be considered operational, and free and open access to data in near real time is anticipated. In addition, the Korean COMS satellite, carrying the Geostationary Ocean Color Imager (GOCI), is planned for launch later in 2009 and will be the first time ocean color is observed from geostationary orbit.

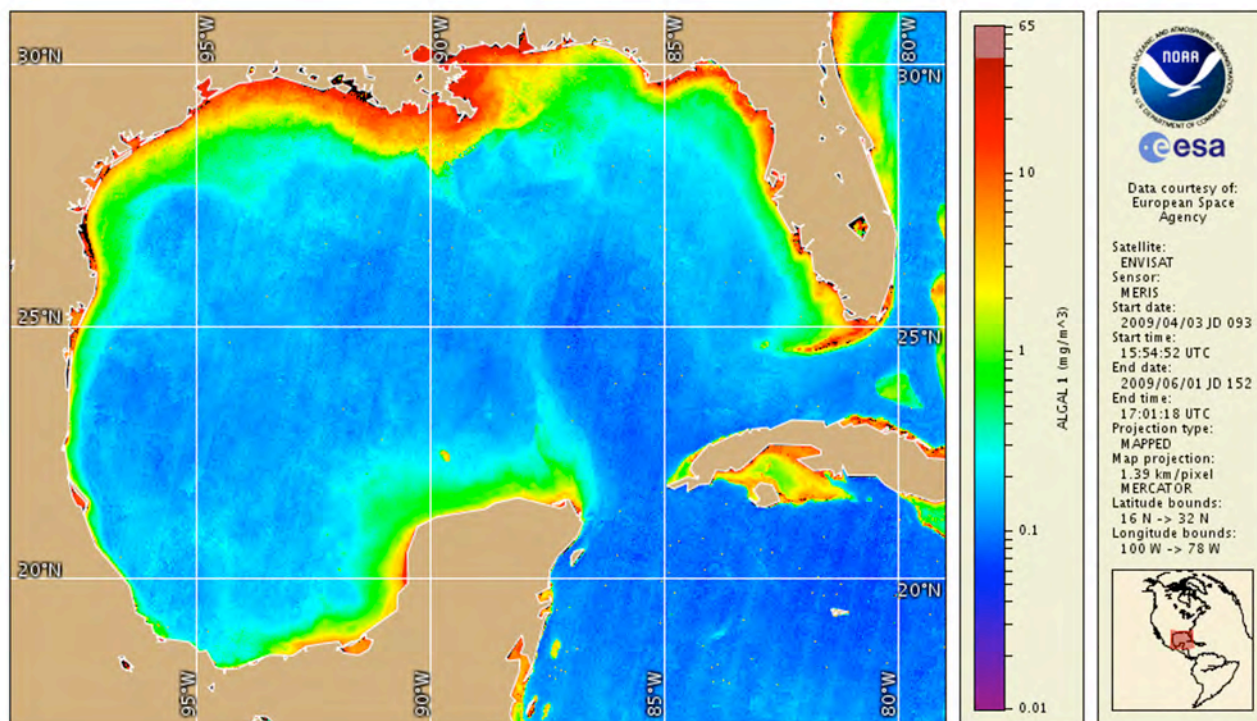


Figure 3: MERIS 1 km ocean color produced operationally by NOAA CoastWatch.

For continuity of U.S. ocean color observations, the VIIRS instrument will fly on the next generation NPOESS environmental satellites, starting with the launch of the NPP spacecraft in 2011. However, VIIRS-NPP may not provide climate-quality ocean color data for the research and applications communities, due to manufacturing anomalies and other issues (see NRC, 2008, for further details). Launch of the operational VIIRS sensor on the NPOESS C1 platform in the afternoon orbit is anticipated no earlier than April 2014. A comprehensive, supporting VIIRS ocean calibration/validation plan is presently being executed as a U.S. government and academic partnership. Additionally, results from improved atmospheric correction using short-wave infrared bands (SWIR) can be applied to the VIIRS instruments and improve retrievals in complex coastal environments (Wang, 2007).

Critical Activities

In addition to the exciting development of these operational ocean color sensors, efforts are underway to develop the next generation of space-based ocean biology and biogeochemistry missions (e.g., hyperspectral instruments), as existing capabilities do not entirely meet the needs of the research and application user communities (see IOCCG, 2008; NRC, 2008). Next-generation missions, both R&D and operational, will likely provide improved spatial, temporal and spectral resolution and coverage. For a comprehensive list of other current and planned sensors providing ocean color data of various resolutions and quality, see the International Ocean Colour Coordinating Group (IOCCG) website (<http://www.ioccg.org>). Cross-calibration is critical for climate applications, and these other sensors have not all been fully calibrated to meet the standard of SeaWiFS data quality.

Ocean Surface Topography

Current Status and a Look Forward

Over the past several years, sea level rise has emerged as one of the most publicly recognizable aspects of the global warming phenomenon. Sea level rise (SLR) directly threatens coastal infrastructure through inundation, increased erosion, more frequent storm-surge flooding, and loss of habitat through drowned wetlands. The only feasible way to resolve the spatial variability needed to accurately determine SLR globally is by means of satellite altimetry, specifically the systematic collection of sea level observations initiated by TOPEX/Poseidon in 1992 and continued today by the on-going Jason series of satellite missions, including Jason-2, launched on 20 June 2008. Jason-2 represents an important step toward the routine measurement of sea level for climate, involving four partners: NASA and CNES are primarily responsible for building and launching the satellite, while NOAA and its operational partner EUMETSAT are primarily responsible for collecting and processing the near real-time data.

In January 2009 Jason-2 and Jason-1 completed a seven-month tandem calibration phase, during which time the two satellites made nearly simultaneous measurements (1 minute separation) along the same orbit. This calibration phase is necessary for identifying subtle performance differences in the many instruments aboard the two satellites and ultimately for creating a sea level climate data record. After a short period of maneuvers, Jason-1 was moved to an interleaved orbit, effectively increasing the resolution of the pair of satellites from 300 km to 150 km in horizontal track spacing and from 10 to 5 days in time. Studies done after one year of operation indicate that Jason-2 is performing at least as well as Jason-1.

Along with Jason-1 and -2, there is presently only one other functioning altimeter in orbit: ESA's Envisat, the successor to ERS-1 and ERS-2. Envisat continues to provide useful sea level data after 7 years of operation although the failure of one RF chain has reduced the satellite to single frequency operation. In October 2008, the U.S. Navy's Geosat Follow-On (GFO) mission was officially ended after a decade of service. The Navy is actively seeking a replacement mission, GFO-2, hopefully to be launched in 2013. The next planned altimeter is Altika, an experimental Ka-band mission jointly supported by CNES and the Indian space agency, ISRO. Altika is scheduled for a late 2010 launch. ESA is planning to launch Sentinel-3, which includes a replacement for the ENVISAT altimeter, in 2012. Finally, NOAA and EUMETSAT are currently in the process of securing funds for a joint Jason-3 mission to be launched in 2013 to overlap with Jason-2.

Because current altimeters provide height measurements only at the nadir location along their ground track and not a 'swath' of data (as is typical of other satellite instruments) there is a trade-off between spatial and temporal resolution. Fortunately, for the large-scale processes generally of interest for climate observations, a single high-accuracy altimetry mission such as Jason-2/OSTM is sufficient. Shorter space and time-scale phenomena at the ocean's mesoscale are not adequately sampled by a single altimeter, but the present configuration of three altimeters in complementary orbits does capture most of the signals of interest. Applications such as ocean eddy monitoring, surface current analyses, and ocean heat content for hurricane intensity forecasting require this

higher resolution sampling (see <http://ibis.grdl.noaa.gov/SAT> for more information on altimetry research and applications). In the next few years, however, it is likely that Envisat will fail and Jason-1 will be terminated to permit a controlled re-entry, leaving possibly only Jason-2 (and perhaps Altika) operating in the near term. The requirement for high spatial resolution coverage may be satisfied by NASA's proposal to fly a swath altimeter (SWOT), but not before late in the next decade.

Critical Activities

By paying careful attention to instrumental and environmental (e.g. path delay) corrections normally applied to an altimeter's range measurements, it is possible to construct a consistent record of global mean sea level change over the past 17 years from the TOPEX, Jason-1, and Jason-2 altimeter missions. As shown in Figure 4, the overall trend for this interval is 3.0 mm/year, roughly 1.7 times greater than the 20th century rate and 3 times greater than the late 1800s – early 1900s rate, both determined from tide gauge observations (Scharroo et al., 2006). Whether the present higher global rate reflects a true long-term change or simply decadal variability is currently unknown.

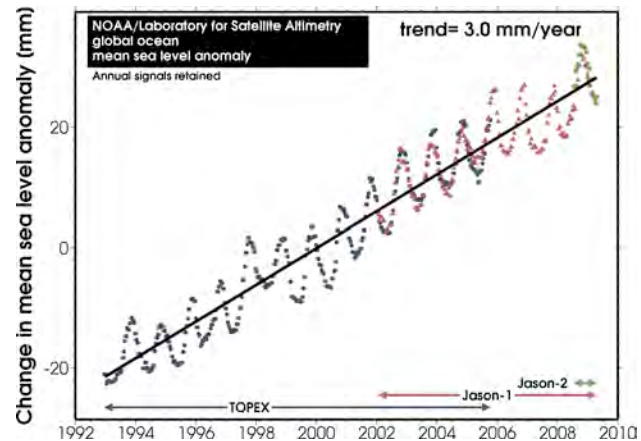


Figure 4: Global mean sea level trend from TOPEX, Jason-1, and Jason-2.

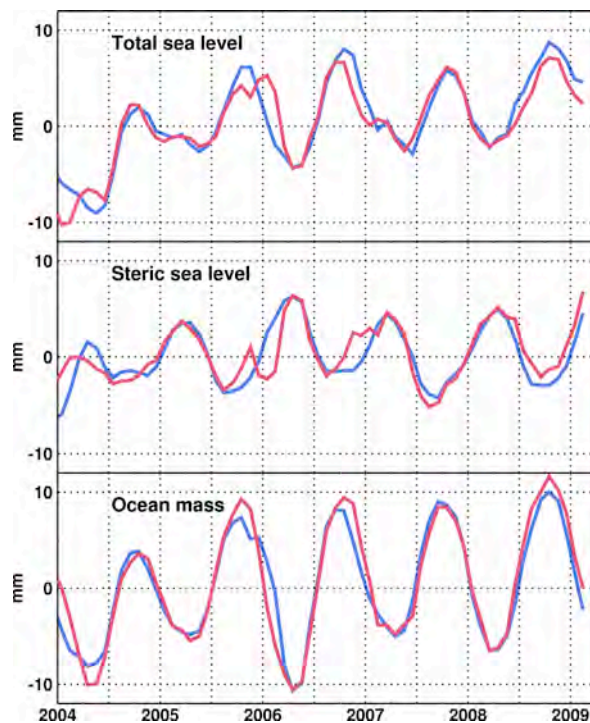


Figure 5: Variability in total global mean sea level and its steric and mass components. The blue lines are the observed (top) total sea level from Jason-1 and Jason-2, (middle) steric sea level from Argo, and (bottom) ocean mass from GRACE in terms of sea level. The red lines show the inferred variability from the complementary observations.

Key to understanding long-period sea level variability is continued monitoring of the sea level rise budget. Changes in total sea level should be equal to the sum of the changes in the components of sea level rise — thermal expansion and salinity changes within the ocean and mass added to the oceans from continental ice sheets. Recent research (Leuliette and Miller, 2009) compared total sea level from Jason-1 altimetry to steric (density) changes in sea level measured by Argo profiles of temperature and salinity and mass variations from the GRACE gravity mission and demonstrated that the budget can be closed for 2004 to 2009. The upper panel in Figure 5 (updated from Leuliette and Miller 2009) shows monthly observations of total sea level computed for five years of Jason-1 measurements. The middle and lower plots in Figure 5 illustrate the budget closure for the complementary observations. Global mean

total sea level trend over the period is +1.8 mm/year, while the trend in the global mean steric component is +0.5 mm/year and estimates of the trend in the global mean mass component range from +1.0 to +1.8 mm/yr. For comparison, the 20th century sea level budget was roughly one-third (0.4 mm/yr) steric increase and two-thirds (1.4 mm/yr) mass increase (Miller and Douglas, 2004).

To ensure accuracy and value of altimeter observations for climate studies, particularly for the global sea level rise problem, it is important to have a period of overlap between satellite missions. Only by directly comparing the average heights between missions is it possible to accurately detect and correct for biases and thereby extend the global sea level record over multiple decades. An overlap is also useful for identifying subtle instrument-dependent problems, such as a drift in one of the environmental corrections to the range measurements. A problem of this type was detected in the Jason-1 microwave radiometer measurements, during the 4-year overlap between the Jason-1 and TOPEX/Poseidon missions, and a recalibrated wet troposphere correction has eliminated the drift.

The value of satellite altimeter observations for climate studies is also greatly enhanced by the operation of two in-situ ocean observing systems supported by the NOAA Office of Climate Observations (OCO): a global network of GPS-controlled tide gauge stations, and the Argo profiling drifter array. Relative sea level observations from more than 80 tide gauge stations are currently providing an independent, ground-based check on the bias and drift errors of each altimeter mission. Routine comparisons between gauge and altimeter measurements show that altimeter-measured trends are accurate within ± 0.4 mm/year. Thus, the 3.0-mm/year trend observed over the past 17 years by satellite altimetry (Figure 5) is significantly higher than the gauge-measured trend over the past century. The gauge measurements may also provide a critically needed solution to the problem of how to deal with gaps in the global mean time series caused by instrument failure or the delay of a follow-on mission.

Sea Ice

Current Status and a Look Forward

Monitoring sea ice is a critical climate indicator, and recent events in the Arctic highlight the need for long-term, continuous observations. The series of passive microwave imagers that began with the Scanning Multichannel Microwave Radiometer (SMMR) in 1978 and extends through the Special Sensor Microwave/Imager (SSM/I) now continues to the present with the Special Sensor Microwave Imager/Sounder (SSMIS) on board the Defense Meteorological Satellite Program (DMSP) F17 satellite. These passive sensors allow for the determination of sea ice extent, but not thickness. Both extent and thickness are needed to determine sea ice volume, which is of fundamental importance to climate models. The NASA Ice, Cloud and land Elevation Satellite (ICESat), launched in 2003, continues to collect ice and snow elevation measurements over polar regions using the Geoscience Laser Altimeter System (GLAS) and is scheduled to remain in operation through 2011. Additionally, ICESat-2, a follow on mission that will exploit more sophisticated instrumentation and sampling geometries to measure sea ice thickness, has a planned launch date in 2013. Before that, ESA plans to launch the CryoSat-2 satellite in December of 2009, which will carry the SAR/Interferometric Radar Altimeter (SIRAL) for measuring ice shelf and sea

ice mass. The CryoSat-2 mission is devoted to the monitoring of sea ice thicknesses and polar ice sheet elevations.

The National Snow and Ice Data Center (NSIDC) continues to update the Sea Ice Index, which uses the combined SMMR-SSM/I-SSMIS record and NASA Team (NT) algorithm to show trends and anomalies (Figure 6) on a daily and monthly basis. The Sea Ice Index (SII) site (http://nsidc.org/data/seaice_index/) is now viewed by about 75,000 distinct users per month in the summer months, reflecting a growing public interest in monitoring changes in the polar regions. Google Earth KML files of sea ice extent and concentration are available as well. NSIDC also produces and maintains monthly Arctic sea ice climatologies based on the National Ice Center (NIC) sea ice charts, which are produced through the analysis of several satellite passive and active data sources. The NIC Arctic climatologies for the period 1972- 2007 are available at <http://nsidc.org/data/g02172.html>. The NIC proposed and secured Navy funding to produce an Operational Sea Ice Index (OSII), parallel to and complementing the passive microwave-based SII, but based on the NIC Interactive Multisensor Snow and Ice Mapping System (IMS) products. The new index will be produced by NSIDC using the 4 km sea ice component of the IMS daily products. The OSII will benefit users who may need a more accurate daily ice edge location than that provided by passive microwave data solely. These users include department of defense, homeland security, and commerce planners, general public, scientists interpreting other data acquired near the ice edge, and researchers seeking to quantify the error in the passive microwave product.

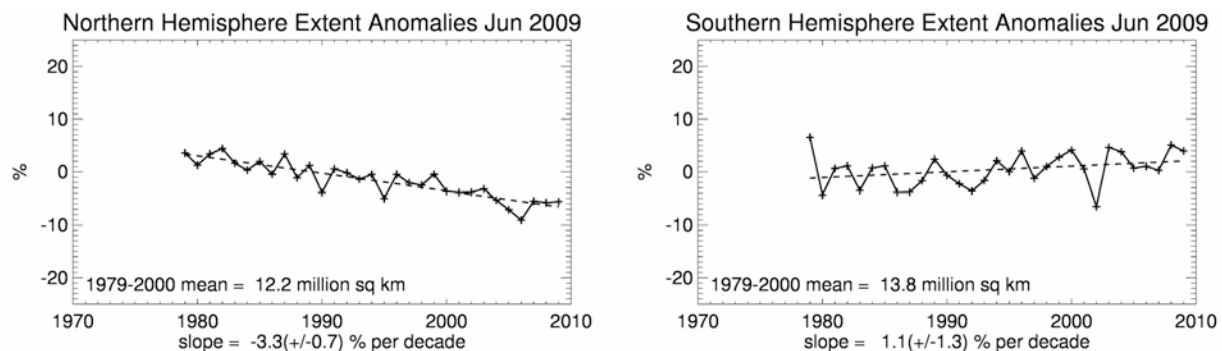


Figure 6: Northern Hemisphere (left) and Southern Hemisphere (right) sea ice extent trends for June from the Sea Ice Index (nsidc.org/data/seaice_index/), based on satellite passive microwave sea ice retrievals.

Although not originally intended for monitoring of sea ice, QuikSCAT, due to its long time series and ability to distinguish between sea ice of different age, has also become an important tool for monitoring the fast changing Arctic sea ice. For example, Nghiem et al. [2007 and 2008] used QuikSCAT to study the extent of Arctic perennial sea ice, the year-round ice cover, and found that it was reduced between March 2005 and March 2007 by 23% with a new record loss in 2008. The rate of loss became more rapid in the 2000s, when QuikSCAT observations were also available to verify the model results. QuikSCAT data have revealed potential mechanisms contributing to the perennial-ice extent loss: ice compression toward the western Arctic, ice loading into the Transpolar Drift together with an acceleration of the Transpolar Drift carrying excessive ice out of Fram Strait,

and ice export to Baffin Bay. QuikSCAT has also recently been used to study other aspects of the sea ice climate data record.

Critical Activities

The dynamic nature of sea ice and the logistical difficulties of conducting in situ measurements on the ice make validation of satellite sea ice freeboard measurements challenging. To address this challenge, the joint NOAA/NASA Arctic Aircraft Altimeter (AAA) Campaign was carried out in March of 2006 using an instrumented NASA P-3 aircraft to underfly Envisat and ICESat satellites. Recent validation studies at NOAA resulting from this campaign have yielded excellent agreement between freeboard heights derived from Envisat radar altimeter (RA2) observations and corresponding estimates made with NASA's Airborne Topographic Mapper (ATM), a well calibrated airborne laser altimeter (e.g. Figure 7). Similarly, excellent agreement has been found in comparisons of airborne laser altimeter measurements with ice and snow elevation estimates from the ICESat GLAS instrument (e.g. Figure 8).

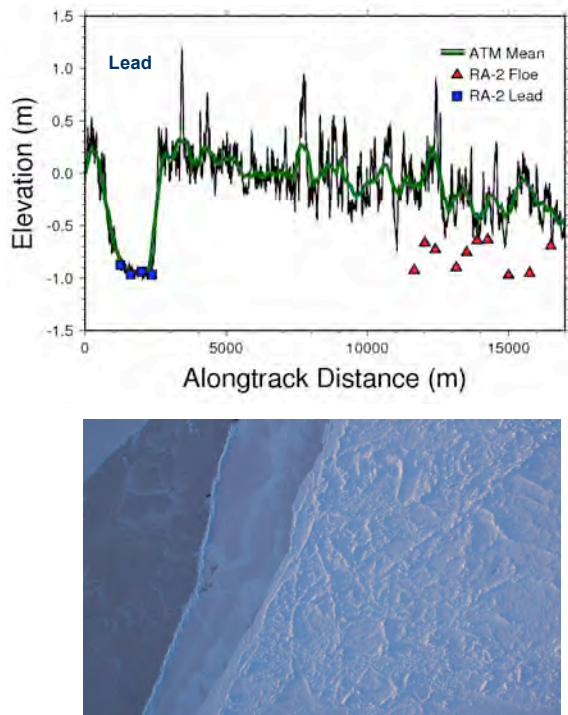


Figure 7. Top panel shows ATM elevation profile along a 17 km Envisat ground track. Blue squares denote Envisat lead locations and red triangles denote ENVISAT sea ice floes. Lower panel illustrates a digital photograph of the lead-floe transition of the upper panel (black box).

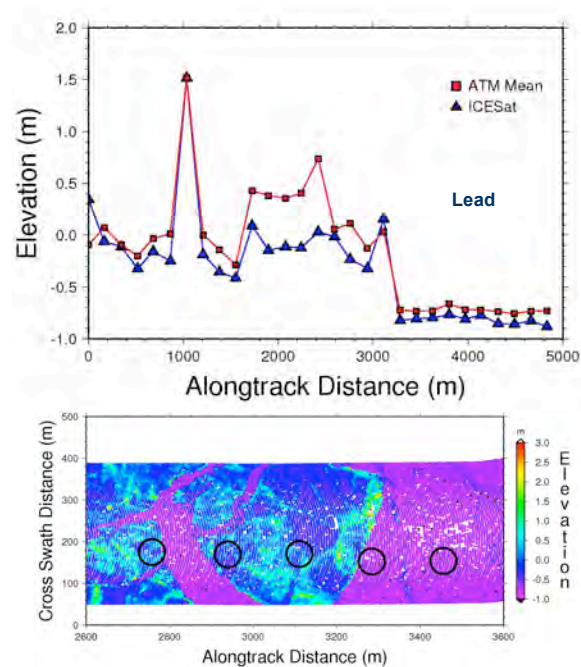


Figure 8. Top panel shows mean ATM elevations (red) and individual ICESat footprint elevations (blue) along a 5 km ICESat ground track. Lower panel illustrates the ATM swath measurements in the sea ice floe – lead transition region bounded by black box in upper panel. The ICESat footprints are denoted as black circles.

A follow on joint NOAA-NASA airborne and in situ experiment was carried out in April of 2009 and included a satellite altimeter under-flight along a track over sea ice in the Canada Basin west of the Queen Elizabeth Islands and over-flights of the Danish GreenArc Ice Camp off the northern coast of Greenland. This Canada Basin Sea Ice Thickness (CBSIT) Experiment was designed to more thoroughly and precisely validate RA2 and GLAS ice freeboard observations and is a NOAA contribution to NASA's Operation Ice Bridge (OIB), an ongoing mission of airborne measurements of Arctic and Antarctic ice intended to help fill the data gap between the ICESat and ICESat-2 satellite missions. NASA HQ has requested that NSIDC assess data management needs for a five-year IceBridge Mission. NSIDC presumes this assessment will lead to an expanded role by NSIDC in IceBridge data management.

Activities of the GCOS SST-SI Working Group are critical to improving concentration estimates from passive microwave data for model assimilation, especially at the ice edge. An algorithm called NT2 uses the higher frequency channels available on SSM/I and later sensors to overcome weather and snow effects, and is being used with AMSR-E data. NSIDC has received funding from the NOAA Scientific Data Stewardship Program to intercalibrate SSMR-SSM/I with AMSR-E, develop data quality fields, and improve metadata and preservation standards. These steps are required to have sea ice extent and concentration meet NRC requirements for CDRs.

It is critical to extend the SSM/I-derived record into the operational life of the NPOESS program's Microwave/Imager Sounder (MIS) instrument. Future MIS sea ice products should be prototyped using AMSR-E in close collaboration with sea ice algorithm and remote sensing experts. The current Aqua satellite has sufficient fuel to operate until 2017. Barring instrument failure, AMSR-E data will be available until then. However the scientific community is still concerned about a data gap should NPOESS be delayed or should Aqua fail sooner.

Synthetic aperture radar (SAR) data and imagery is another valuable tool for monitoring sea ice in near-real time, as well as assessing its seasonal and interannual variability in the context of climate variability and change. While there are currently numerous satellite sensors such as ASAR on Envisat and PALSAR on ALOS providing such data to users, and likewise plans for continuity internationally (e.g., Sentinel-1, Radarsat constellation), routine and sustained access to data for U.S. research and applied users is an ongoing concern as the U.S. does not currently have its own SAR sensor/mission.

Marine Winds

Current Status and a Look Forward

While NSCAT on ADEOS and SeaWinds on ADEOS II operated for a total of only 18 months, QuikSCAT has provided over 10 years of continuous high quality global ocean surface wind measurements. The ASCAT on MetOp is currently in its third year of operation and provides approximately 60% of the daily coverage of QuikSCAT with a retrieval spatial resolution that is twice as coarse. WindSat continues to function and provide wind vector data at about 50% the coverage of QuikSCAT at a spatial resolution that is 4 times as coarse. The WindSat wind vector retrievals are also less accurate in the lower wind speed regime ($< 7\text{m/s}$) and are limited in the storm environment. The passive MIS instrument is the replacement for the Conical Microwave

Imager/Sounder (CMIS), which was originally planned to be part of the NPOESS mission but was removed from the program. The MIS will continue the SSM/I and SSMIS legacy on NPOESS and is scheduled for a 2016 launch. NOAA is pursuing collaboration with the Japanese Aerospace Exploration Agency (JAXA), where NOAA would provide a Dual-Frequency Scatterometer (DFS) system to fly aboard JAXA's GCOM-W2 and GCOM-W3 missions.

A notable oceanographic climate result enabled by the long QuikSCAT time series was presented by Lee and McPhaden (2008), who studied the implications of the QuikSCAT and ERS winds and altimeter sea surface height observations to decadal variability and connections of oceanic and atmospheric circulations in the Indo-Pacific region, as shown in Figure 9. The observed wind patterns explain the observed sea level pattern through local Ekman pumping and westward propagation of Rossby waves. In particular, the scatterometer and altimeter data suggest an anti-correlated decadal variability of the meridional overturning circulations (MOCs) and heat transports in the Pacific and the Indian Oceans, such that the Pacific- and Indian-Ocean MOC play opposite roles in regulating tropical heat content that is important to interannual and decadal climate variability. The observations also highlight the oceanic tunnel via the Indonesian throughflow and atmospheric bridge through the Walker Circulation in connecting the Indo-Pacific variability. This kind of improved understanding of the climate system is becoming more possible with the improving length and accuracies of the available satellite-based data.

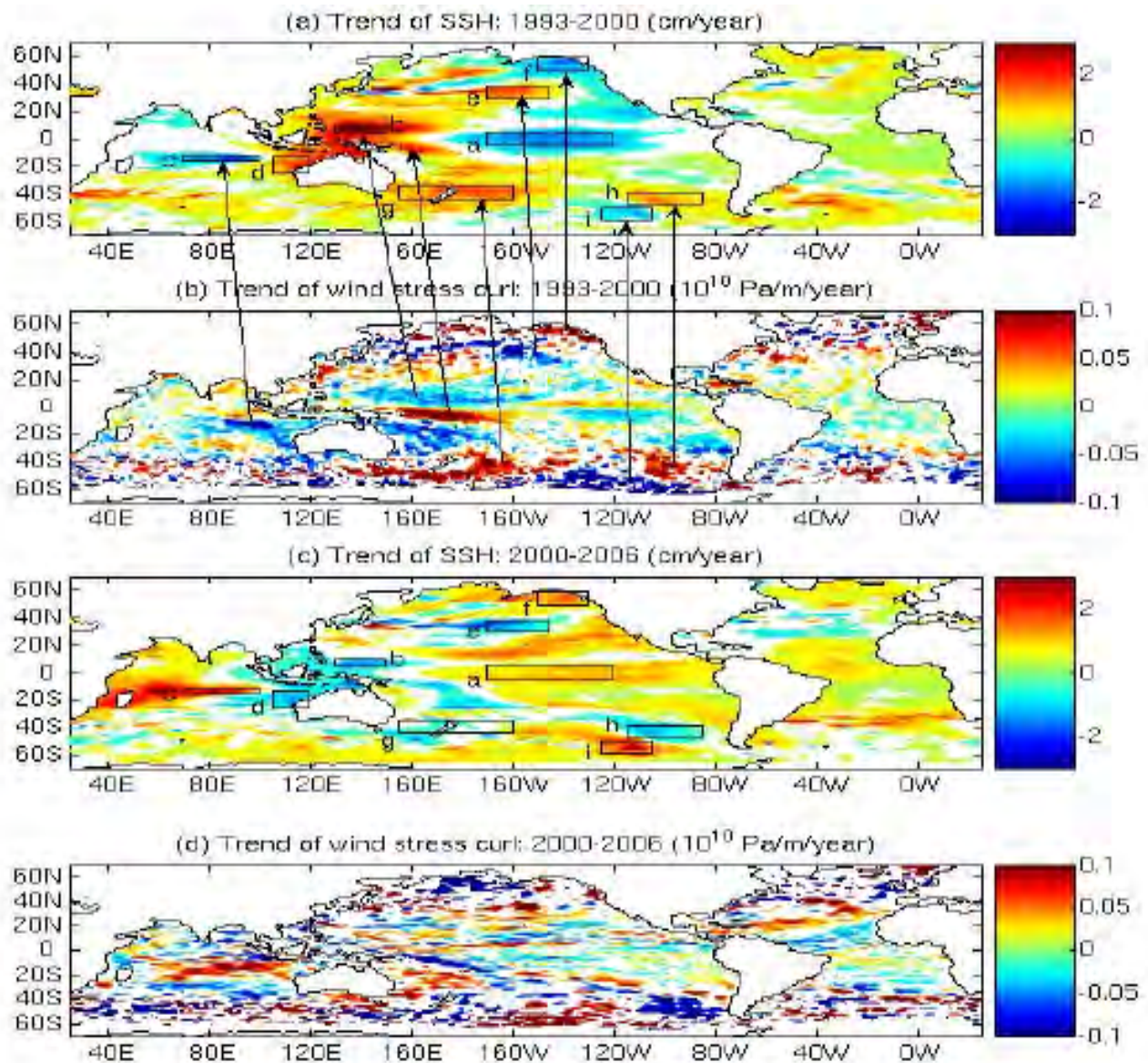


Figure 9. Decadal tendencies in the 1990s and 2000s are opposite in sign in much of the Indo-Pacific domain for wind (ERS and QSCAT) and sea level (T/P and J1). The wind patterns explain the sea level pattern through local Ekman pumping and westward propagation of Rossby waves. From Lee and McPhaden (2008).

Critical Activities

The remarkable duration of the QuikSCAT mission has brought satellite measurement of ocean wind fields into the realm of climate science, allowing CDR production to be routine on a weekly and monthly temporal basis, such as the weekly and monthly QuikSCAT global wind fields created by the NASA Physical Oceanography Distributed Active Archive Center (PODAAC) and Remote Sensing Systems. Prior to QuikSCAT, the measured global ocean surface wind vector field was scattered temporally and spatially at best, with ERS-1 and ERS-2 offering globally distributed

measurements, but with a narrow swath. QuikSCAT now has an unprecedented ten years of continual operations, but has no reliable U.S based replacement set to compliment or continue this record production.

The decade-long ocean vector winds data record has enabled a number of climate studies and results not possible without QuikSCAT's contribution. For the first time, a number of climatologies have been developed to help characterize winds over the ocean. For example, Risien and Chelton (2006, 2008) provide an interactive Climatology of Global Ocean Winds based on 5 years (August 1999-July 2004) of QuikSCAT satellite measurements of wind speed and direction, as well as their spatial derivatives (wind divergence and stress curl), and show that persistent small-scale features resolved by the QuikSCAT data demonstrate that surface winds are influenced by topography, SST gradients, and ocean currents.

A meaningful CDR wind field requires a reasonably unbroken and accurate data source. The ASCAT instrument on the first of the MetOp satellites launched in October 2006 compliments the present ocean wind field climate record and helps partially mitigate a gap in the data records. Also of significance is the cross-validation of different surface wind measuring platforms, such as the C-band ASCAT scatterometer, the Ku-band SeaWinds scatterometer, and more varied instruments such as the polarimetric radiometer WindSat. Included in this is more sophisticated validation of measurements of extreme environmental events, such as strong extra-tropical storms and hurricanes, with more localized measurements using similar scatterometers and radiometers aboard NOAA WP-3D aircraft. Looking toward the future, the continuity of wind vector CDRs requires a commitment to a series of fine spatial resolution, broad swath scatterometer systems that will provide accurate wind vector retrievals from calms to the strongest hurricane winds, including coastal winds where significant ocean upwelling occurs. The realization of DFS on GCOM-W2 and GCOM-W3 will be a significant step toward a sustained wind vector CDR capability, where DFS provides both the C-band and Ku-band channels and improved spatial resolution.

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